The Ladder Spoke Resonator at INFN-Legnaro

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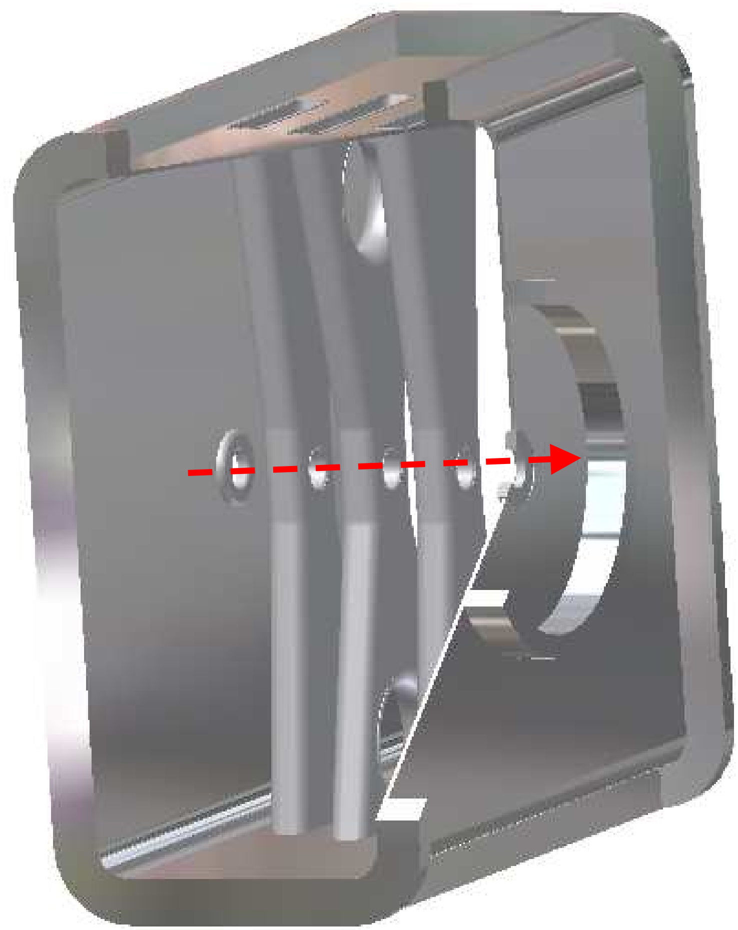
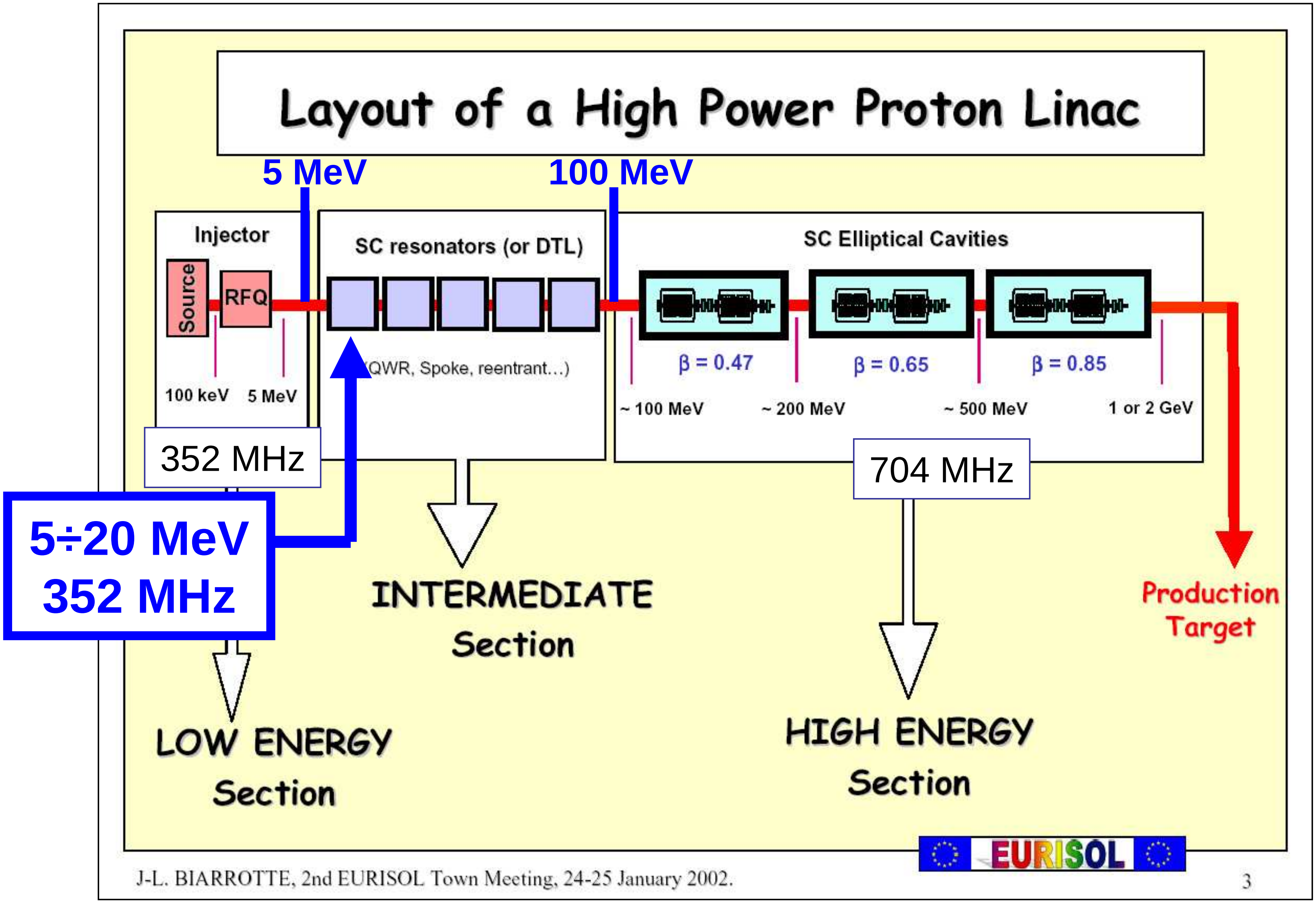


An easily accessible SC resonator
for a **5 mA proton accelerator**
352 MHz, 4 gaps, β_0 = 0.12 & 0.17,
5÷20 MeV range

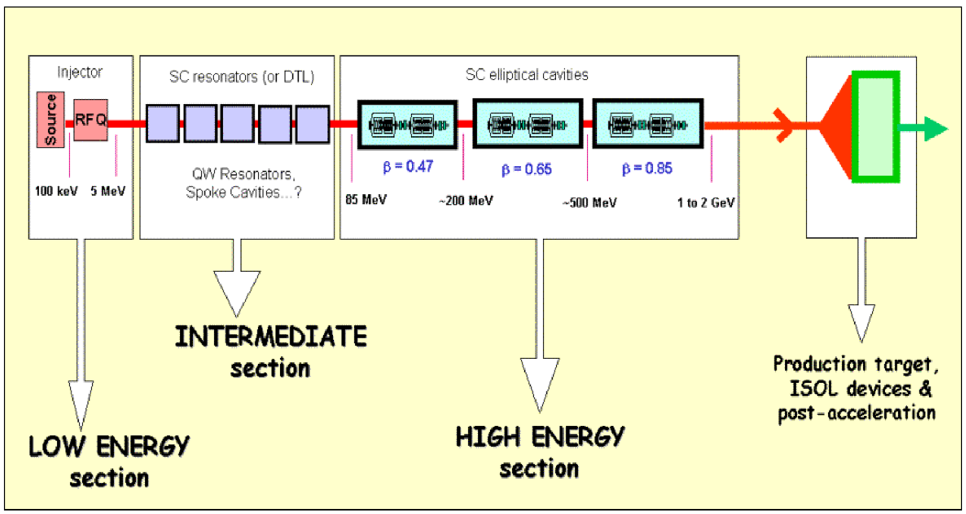
Framework
Linac design
E_z flatness = B-field = Large flanged joints
= RF Coupling = f-tuning
Outlook

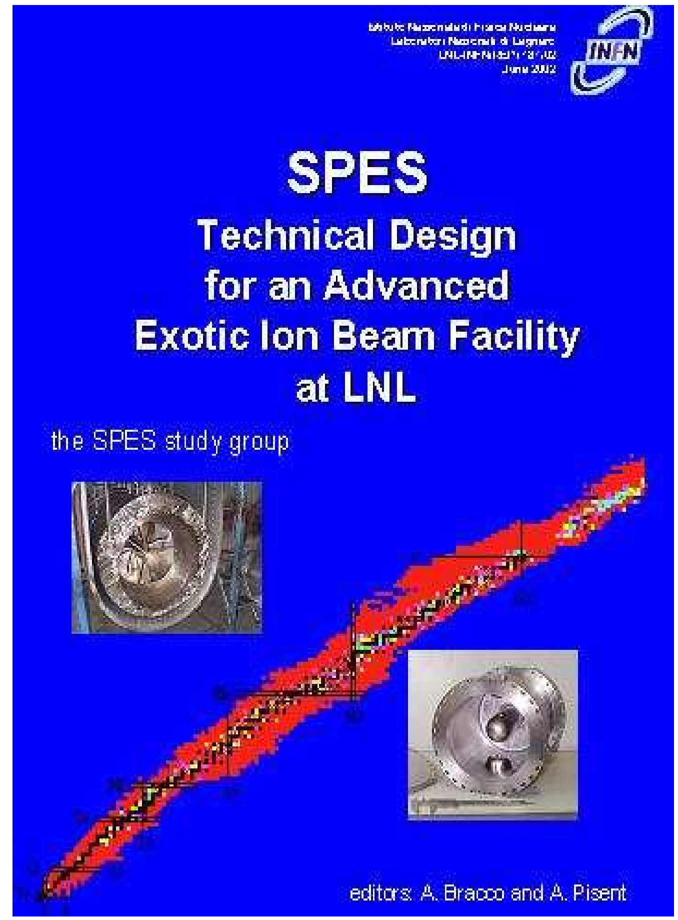
Framework: β = 0.1÷0.2 SC cavities for 5 mA p linac



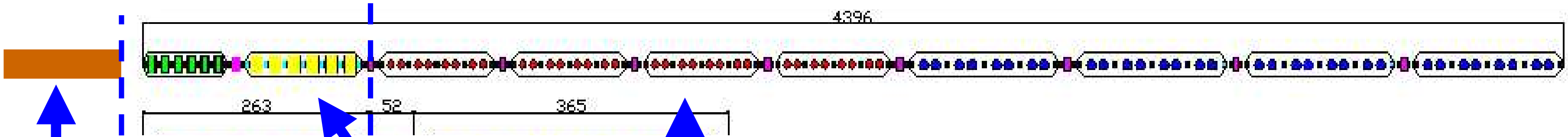
5 mA p superconducting linacs for RIBs production (but also ADS demonstrators..)

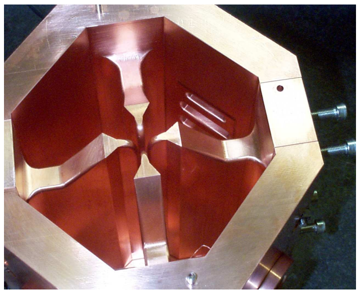
DRIVER ACCELERATOR for EURISOL

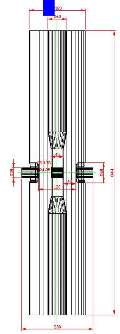




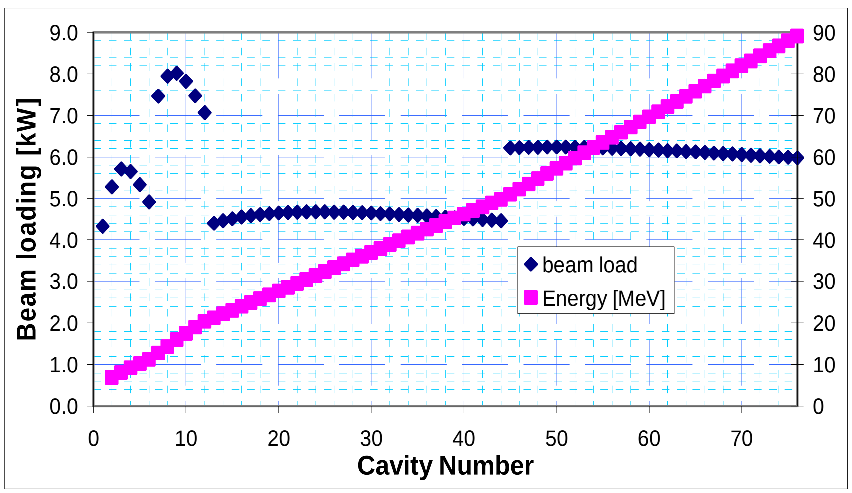
5 mA superconducting linac (SPES-EURISOL)



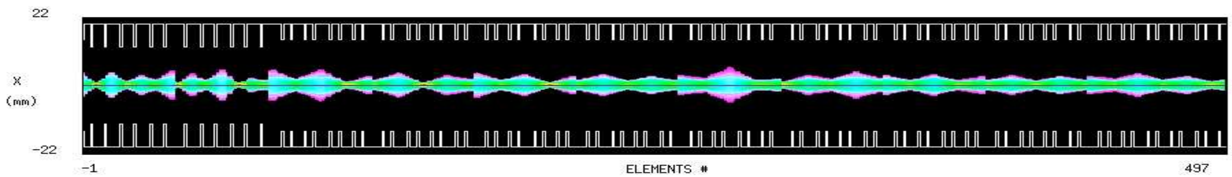




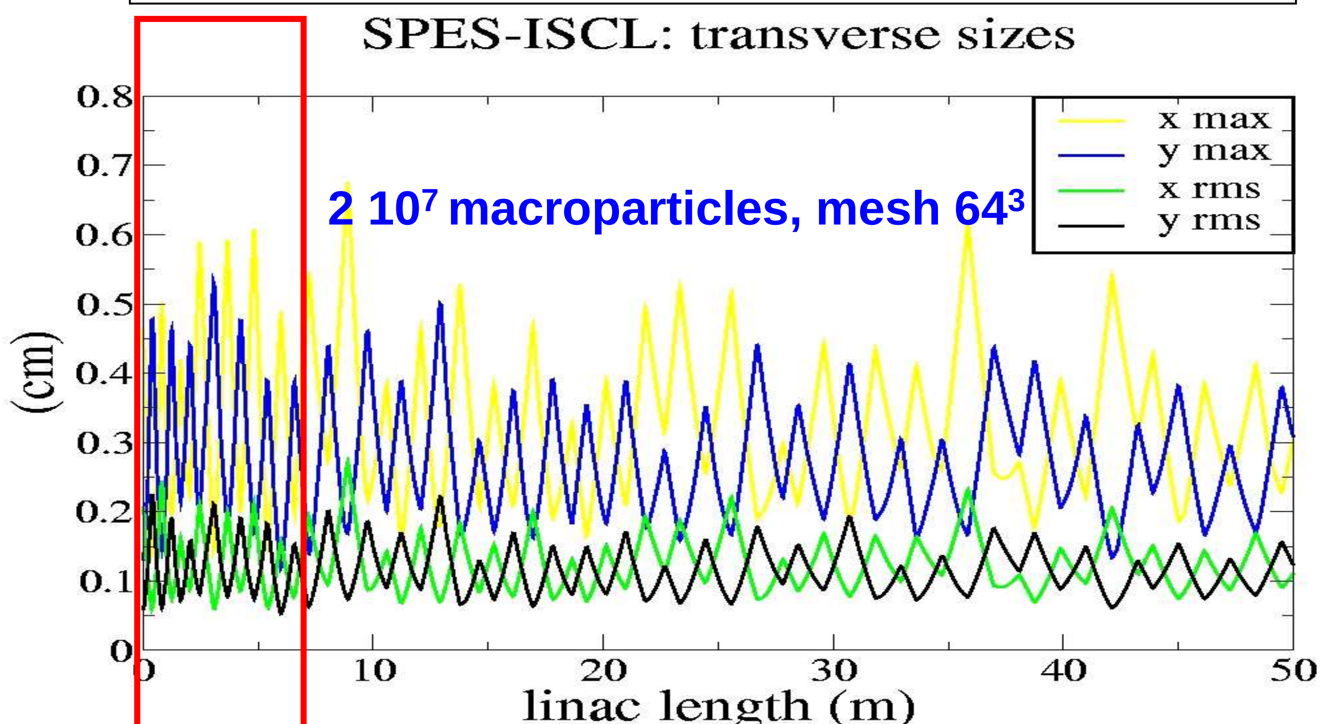
Total length	44	m
Final energy	89	MeV
Synchronous phase min/max	-35/-25	deg
Average acceleration	1.90909	MeV/m
Number of cavities	76	
Number of Quadrupoles	54	
Max. Quadrupole gradient	40	T/m
Quad aperture/length	2/5	cm
Current limit (losses<10-5)	>50	mA
RF dissipation	760	W(@4.5K)
Beam loading	420	kW
RF sys. pwr. cons. (h_{RF}=50%)	840	kW
Static cryo. losses (10 W/m)	440	W
Cryo. sys. cons. (h_{cryo}=1/500)	600	kW
Mains power	1440	kW



Beam Envelopes with the 5 mA p beam



$\varepsilon_{T,in}$(norm) = 0.2 mm mrad, $\varepsilon_{L,in}$ = 0.2 MeV deg



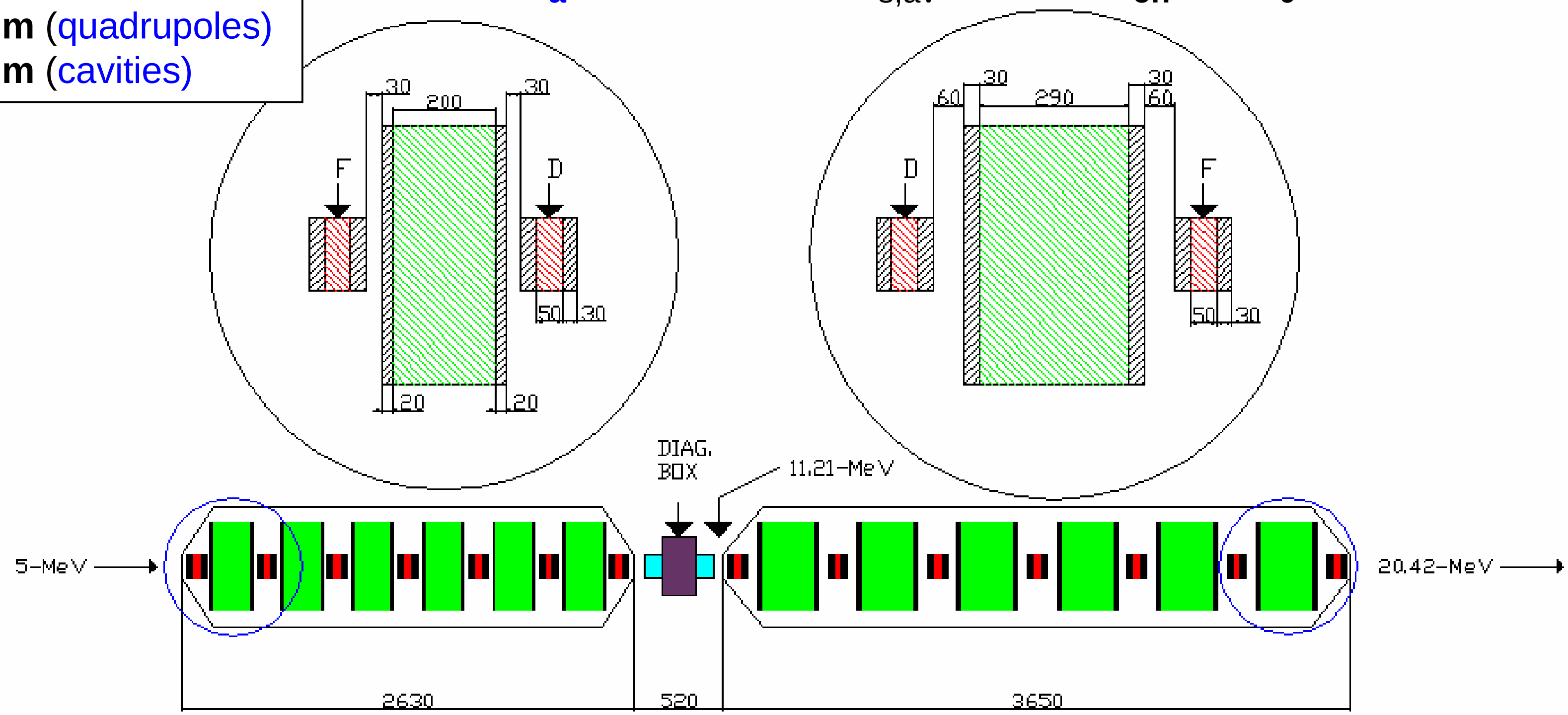
2 10^7 macroparticles, mesh 64^3

(Section with **12 ladder resonators**
5÷20 MeV, Length = **7 m**)

Twelve 4-gap Resonators in 2 Cryostats

Beam bore Ø:
40 mm (quadrupoles)
25 mm (cavities)

Needed **E_a = 5.8 MV/m**, $\phi_{s,av}$ = -30º, **L_{eff} = 2$\beta_0\lambda$**

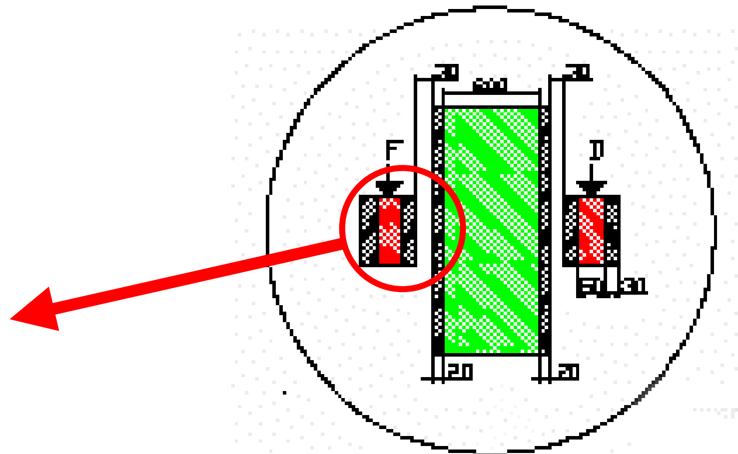


β_0 = 0.12

β_0 = 0.17

Strong transverse focusing in the first cells (97º per FODO)
to avoid the fast exponential growth of the **parametric resonance**

The focusing element: a superferric quadrupole



A Superferric Quadrupole for use in an SRF Cryomodule, F. Zeller[1], J. C. DeKamp[1], A. Facco[2], T. L. Grimm[1], J. Kim[1], and R. Zink[1]
[1] ***NSCL-MSU*** [2] ***INFN - LNL.***

Properties

Effective length 50 mm

Radius 20 mm

Gradient 31 T/m

Current (2-D calculation) 63 A

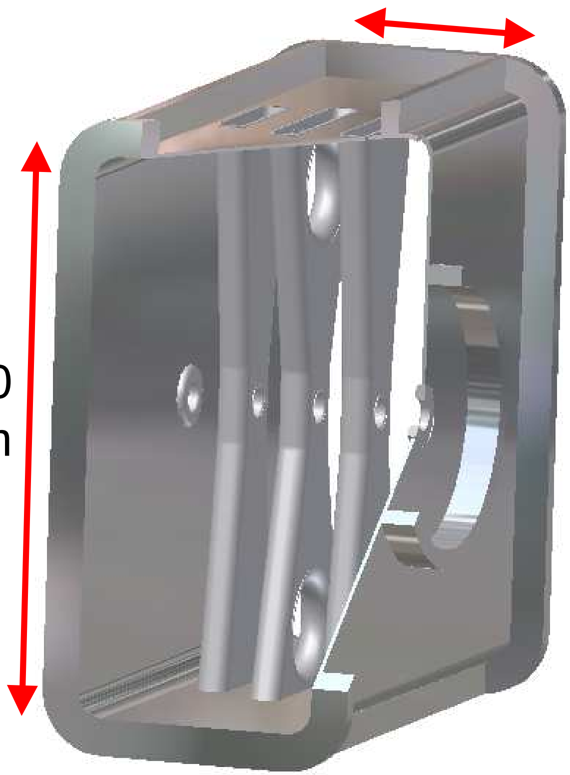
H_q field in the resonator < 0.05 mT

Why quadrupoles? **Homogeneous** to preceding RFQ and following linac scheme
With respect to QP-doublet and Solenoid, easier matching with the RFQ

The 4-gap Ladder Resonator

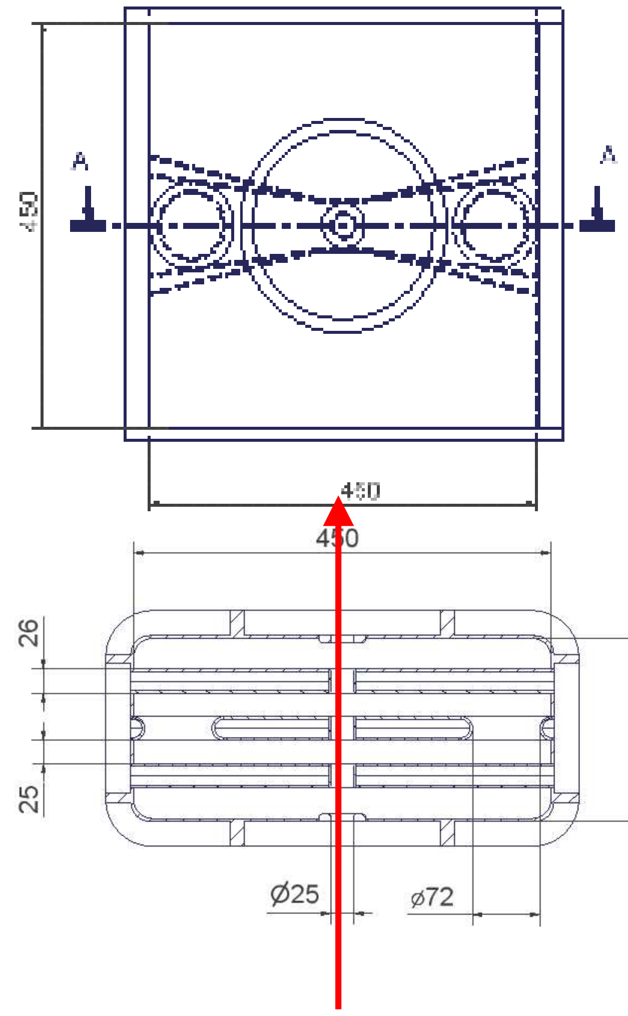
L_{int} = 200 mm

450 mm



Huge flanged ports for:

- Inspections
- Repair (grinding and EBW)
- BCP and rinsing



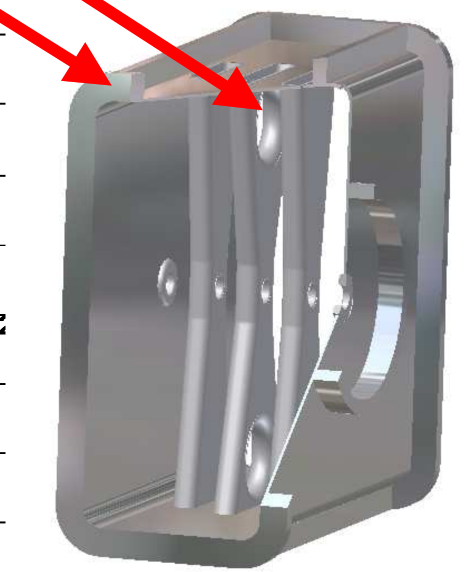
Three stems (four gaps)
Stems have a racetrack cross-section

- from 65 mm to 125 mm (1st and 3rd)
- from 65 mm to 166 mm (2nd), with two 72 mmØ coupling holes

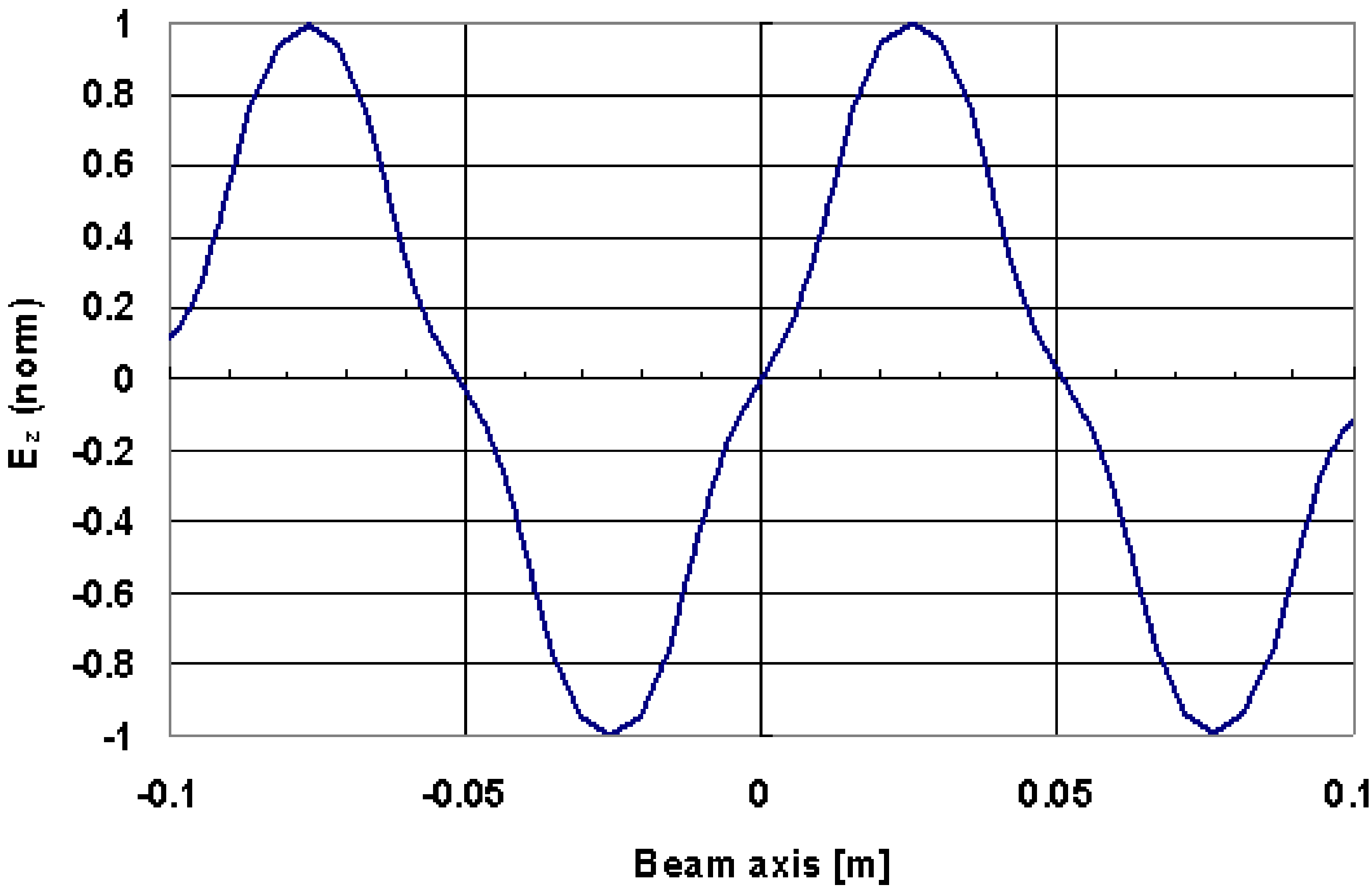
Beam bore 25 mm, Gap length 25 mm

Ladder Resonator (β_0=0.12): rf parameters

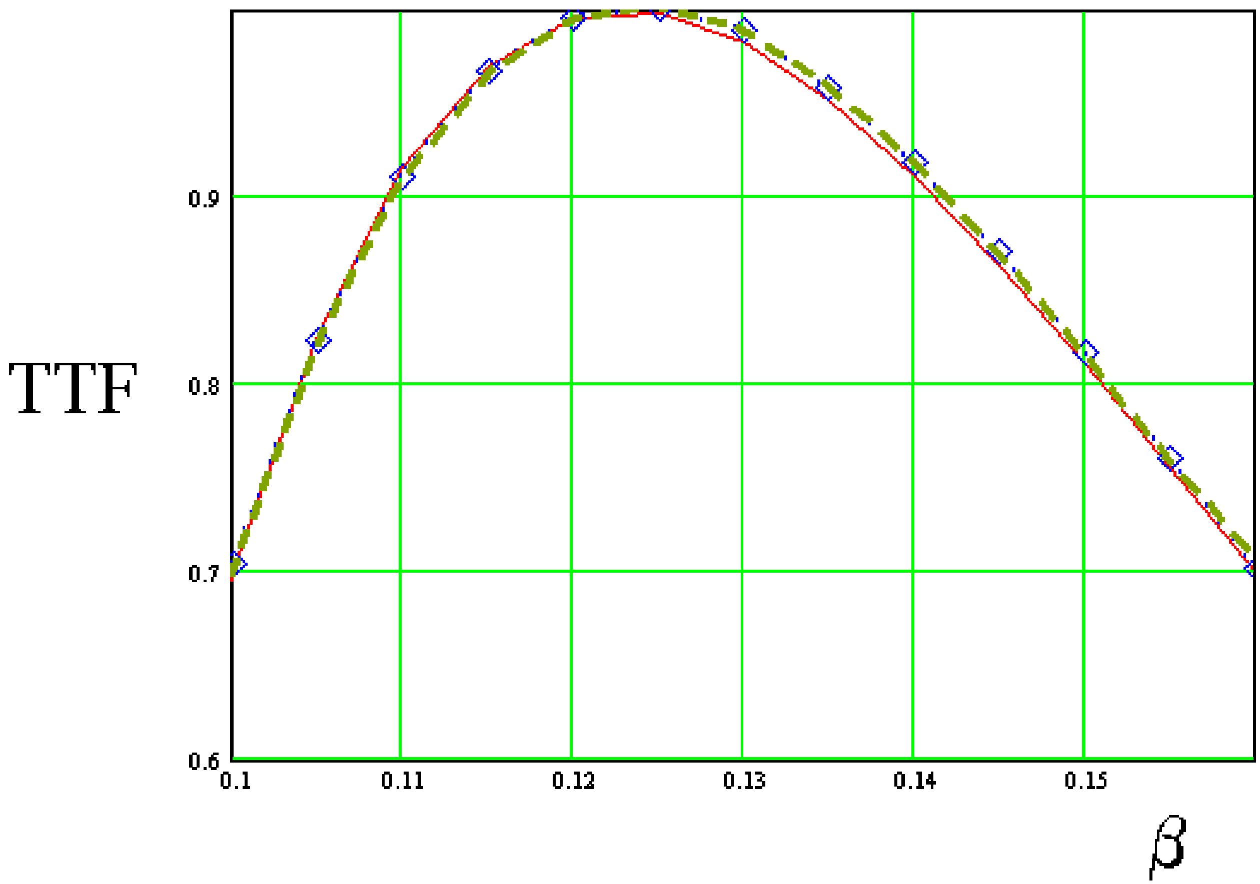
Frequency	352 MHz
Accelerating field flatness (between central and end cells)	100 %
$B_{s,p}$	65 mT (set as limit) @ the coupling hole
B at the flanged joint	1.5 mT
$E_{s,p}$	20 MV/m
Energy gain at β_0 = 0.12	1.15 MeV/q
Accelerating Field E_0	5.8 MV/m
Beam Loading	4.2÷5.8 kW
U/E_a^2	59 mJ/(MV/m)^2
Rf coupling (coupling holes)	1.2 %
Q - @ 4 K (assumed)	5 x 10^8
Geometrical factor G (Ω)	45 Ω
$B_{s,p}/E_0T$	11.2 mT/MV/m
P_{diss} (@ Q = 5 x 10^8)	10 W



Field Uniformity on Beam Axis = 100%

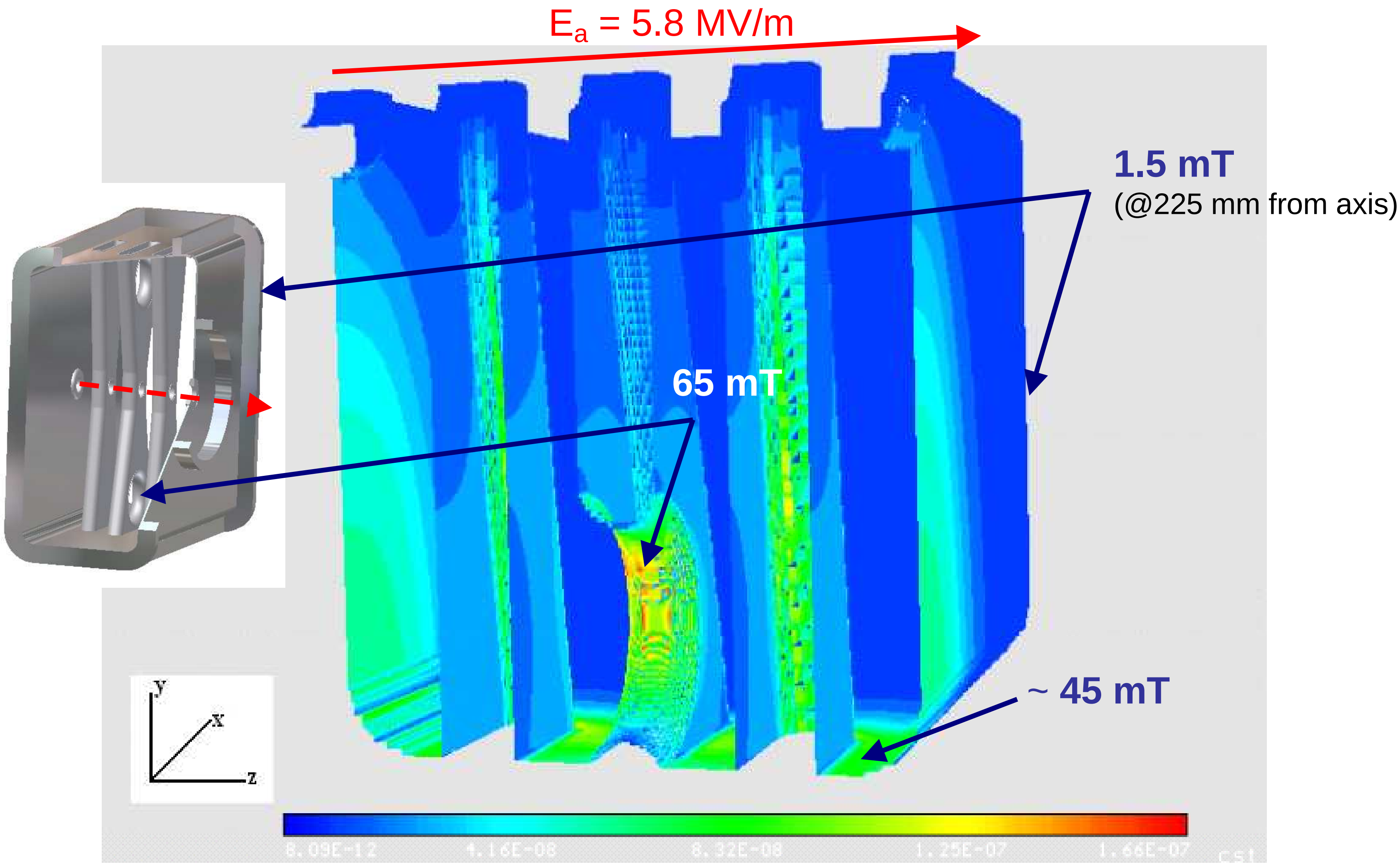


β_0 = 0.12 Ladder: TTF curve

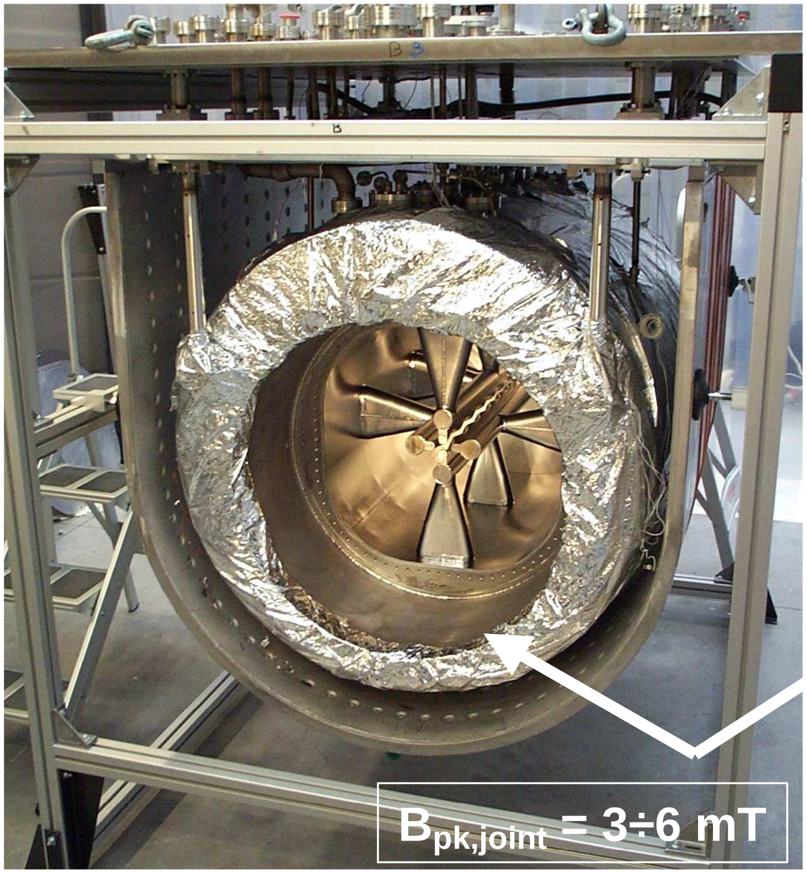


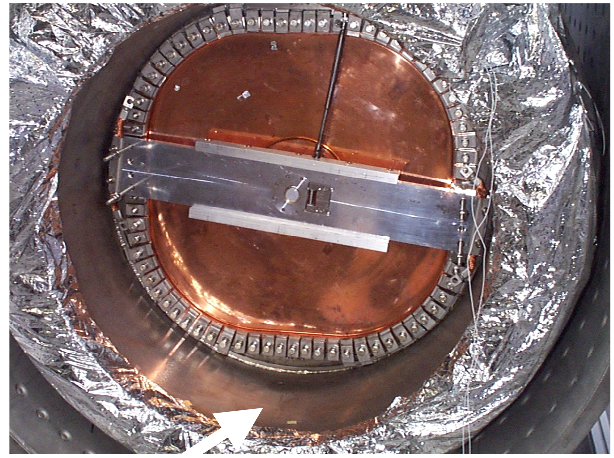
TTF curve of the ladder resonator (blue diamonds),
plotted together with the polynomial approximation (eq. (1), green dash curve)
and the 4-thin-gap approximation (eq (2), red solid curve).

Distribution of Surface Magnetic Field

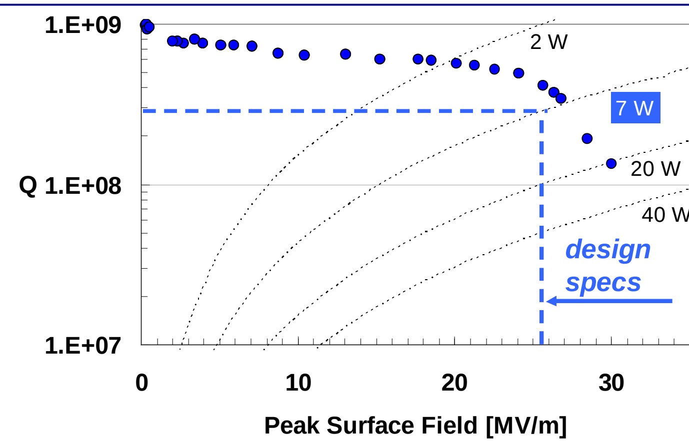


SC Joint on SC-RFQ at INFN-LNL

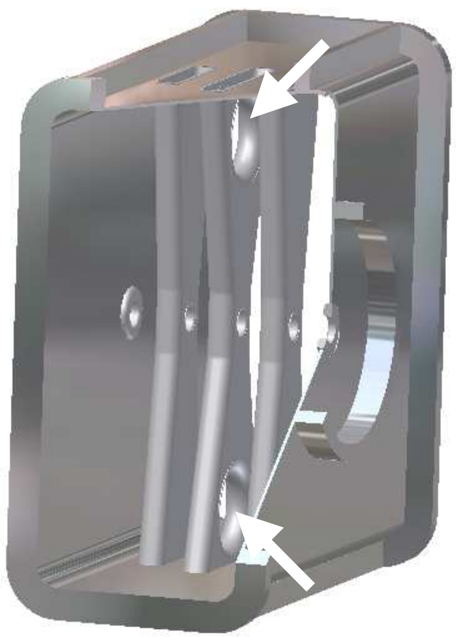


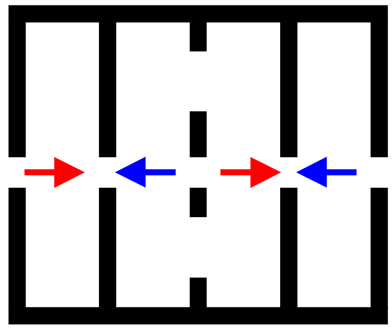


Nb/Cu sputtered end-plate (no gasket, just pressure – **see also** **K.W. Shepard, IEEE Trans. on Nucl. Sci., NS-24, N.3, June 1977, 1147**

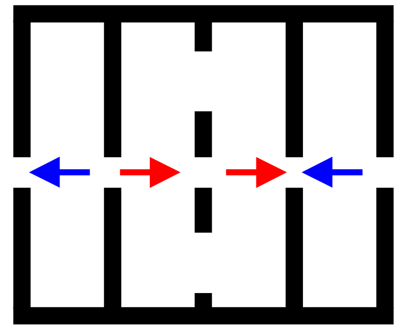


RF Coupling

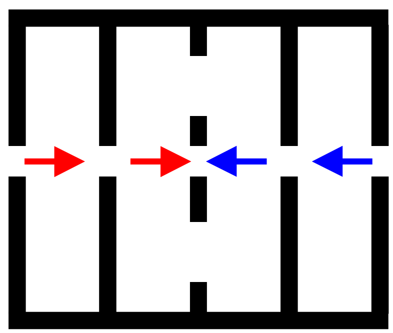




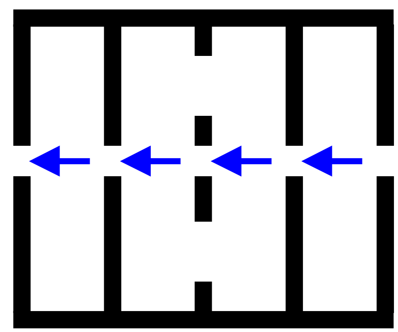
f_0 = 352 MHz (w.m.)



f_1 = 356.3 MHz



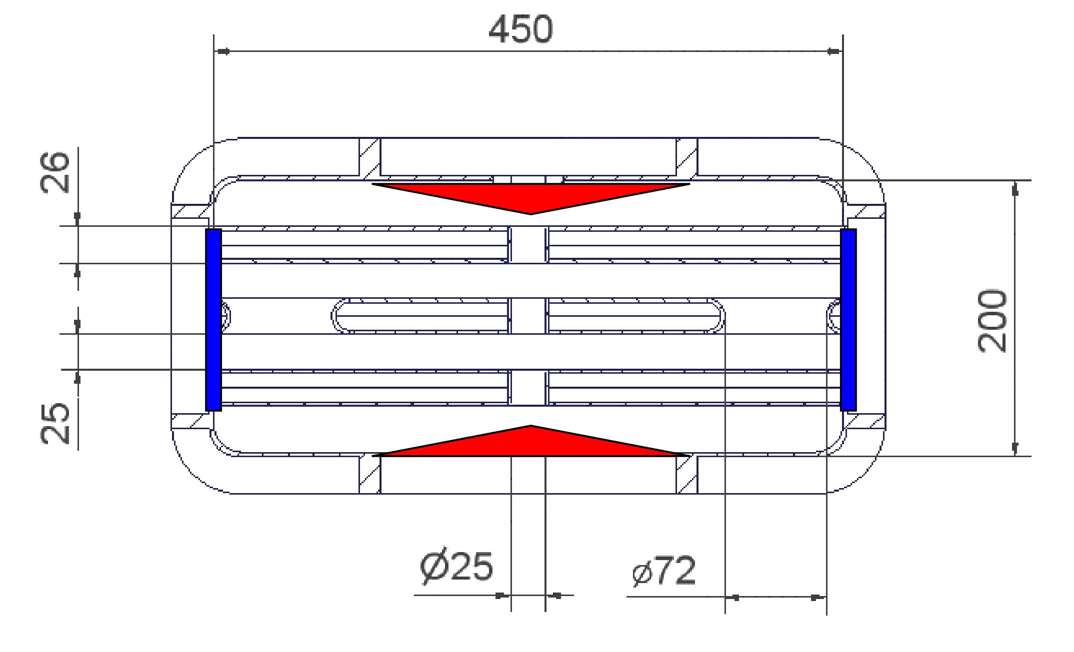
f_2 = 357.2 MHz



f_3 = 449.1 MHz

Without coulping holes:
Gap length very small vs.
stem width → mode degen.
With holes: 1.2 % coupling
Positioning error of one stem
by 0.1 mm in z →
1% deviation in E_z flatness
(and mode separation +1.5%)

Frequency Tuning



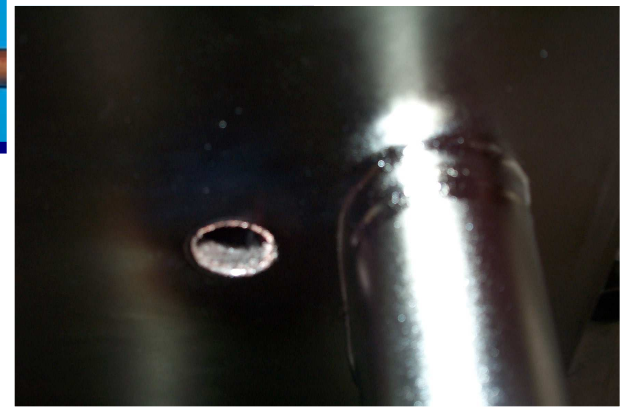
Rough Tuning (**during construction**): stepwise reduction of stem length (both sides)
+1.33 MHz/mm

Fine Tuning (**in operation**): end-plate deformation (both sides)
-1.08 MHz/ (0.1mm)

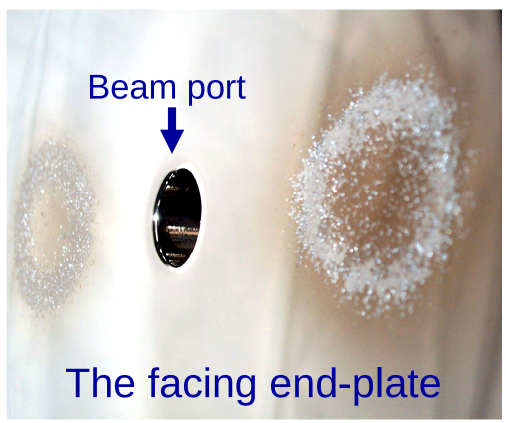
Outlook

- **Compact acceleration** of a **5 mA** p beam (12 cavities, 2 cryostats, 7 m): **5÷20 MeV (β = 0.1÷0.2)**
- The Ladder scheme allows **ample access** for **inspection, repairs and treatments** while retaining **good rf properties**

  (100% field flatness, E_{pk}=20 MV/m, H_{pk} = 65 mT, E_a = 5.8 MV/m)
- Mode degeneration is overcome by **rf coupling holes** in the central stem
- **Next steps**: **mechanical analysis**, EBW and **construction tests**, definition of **tuners** and **rf ports**, design of the **liquid He dewar**

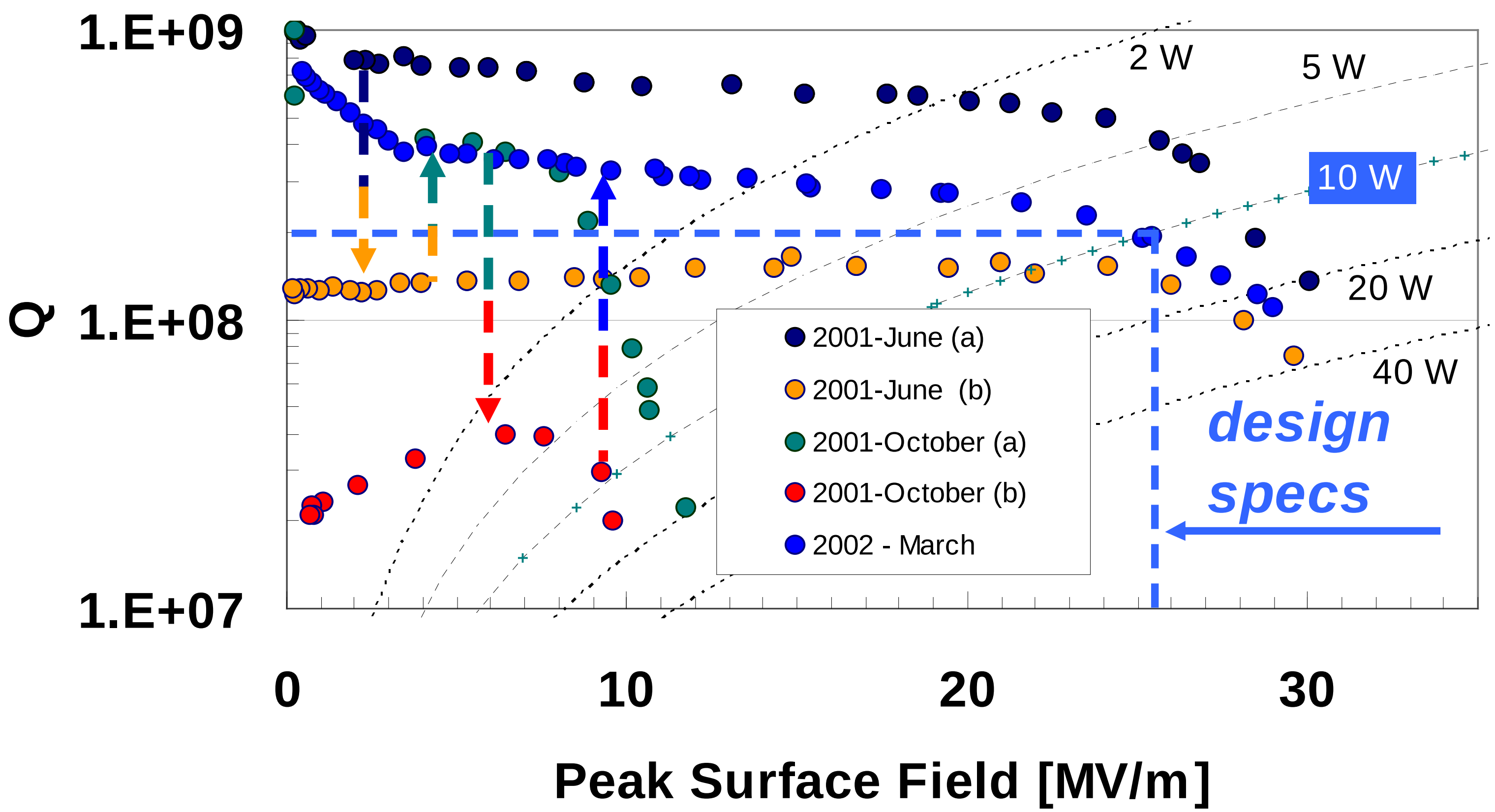


- Plasma discharge: sputtering of Cu and INOX layer in a high-j region
- Chemical Polishing would have taken months
- **No CP**, 3M – Scotch Brite **lapping followed by HPWR** (2 weeks)

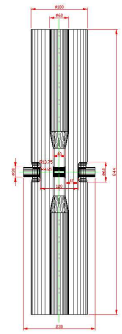


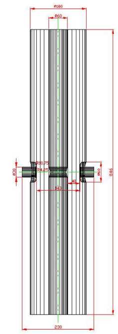
- **CP** again **avoided**
- 3M – Imperial**, with Al_2O_3 abrasive (60 to 2 μm)**
- **HPWR**

Evolution of SRFQ2 Performance



Superconducting cavities





Cavity type	4-gap	4-gap	HWR	HWR	units
β_0	0.124	0.17	0.25	0.33	
n. of gap	4	4	2	2	
E_p/ E_a	**~3.**	**~3.**	**~4**	**~4**	
H_p/E_a	**102**	**100**	**95**	**106**	**Gauss/(MV/m)**
$R_s \times Q$	45	62	54	66	Ω
Eff. length	0.2	0.29	0.18	0.214	m
Bore diameter	25	25	30	30	mm
Design E_a	6	6	6	6	MV/m
Design energy gain	**1.2**	**1.74**	**1.08**	**1.284**	**MeV/q**
n. required	6	6	32	32	

Linac compactness at low β

Δ**W**: maximum acceleration/cavity is desired for economy reasons

Parametric resonance $\sigma_L=2\sigma_T$ must be avoided (<u>width</u>: 0.4" σ_T/σ_L" 0.6)
σ_T " $\pi/2$ (**envelope instability**)

Consequently: $\sigma_L = \sigma_T/0.4$ **= π/0.8.** But:

$$\sigma_L \approx L\sqrt{\frac{en\Delta W}{mc^2 L}\,\frac{2\pi\sin(-\phi_s)}{\beta^3\gamma^3\lambda}} \propto \sqrt{L}$$

(E average accelerating field, n number of cavities per period, $\beta-\gamma$ relativistic parameters, λ rf wavelength)

Given cavity no. and energy gain, there is a limit on the period length **L**

A **compact lattice** is needed **for high performance cavities**

Linac lattice

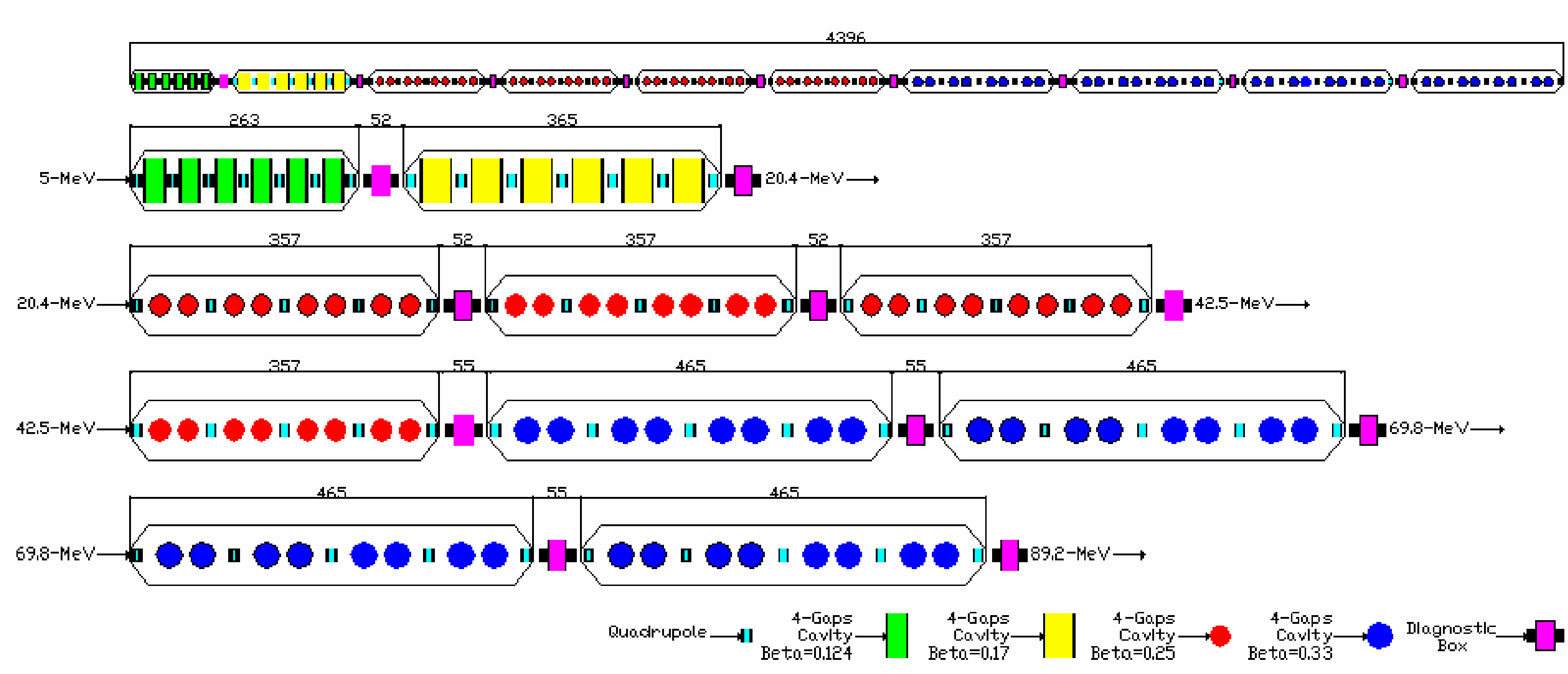
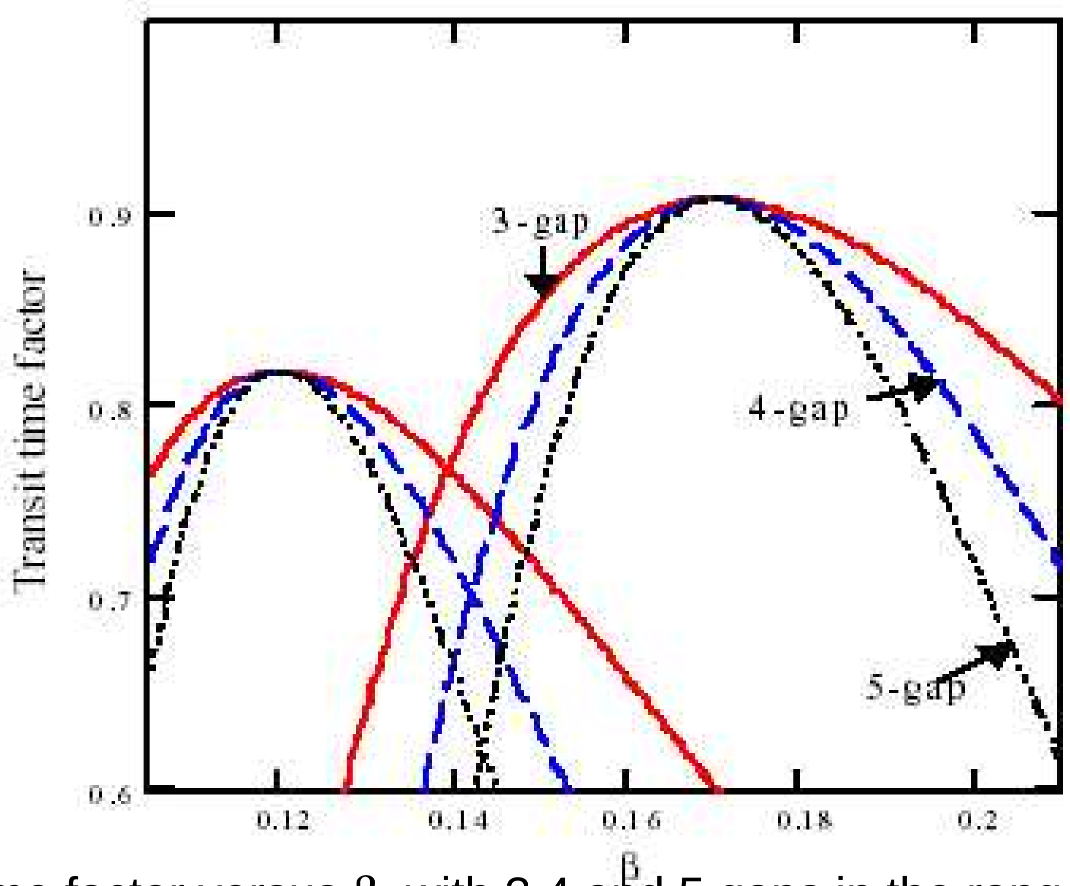


Figure 1 *Linac layout*

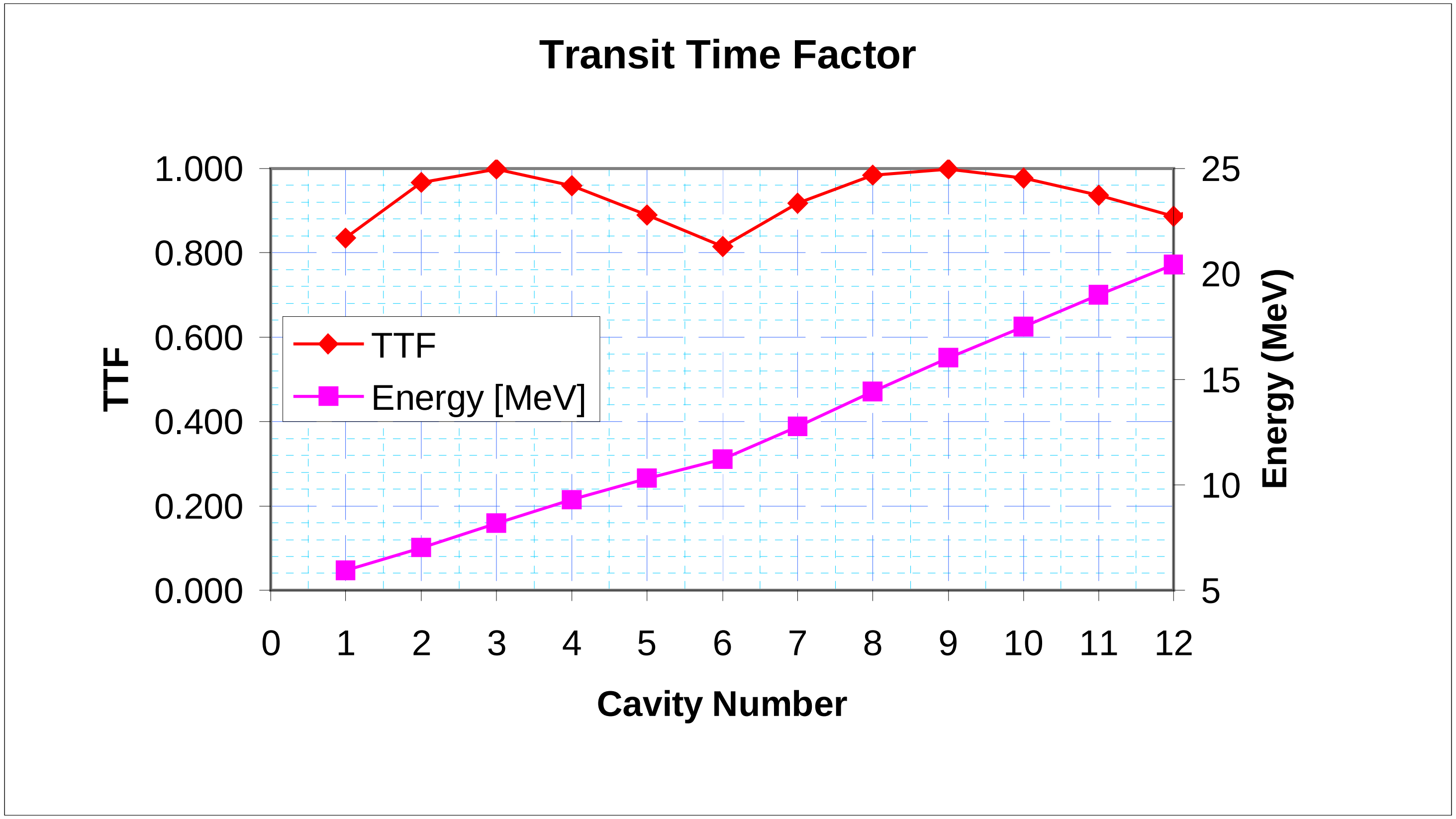
Length = 44 m, 10 cryostats, 76 resonators, E_{fin} = 90 MeV

Choice of the number of gaps in the desired beta range



Transit time factor versus β, with 3,4 and 5 gaps in the range b = 0.1÷0.2

TTF and Energy along the linac



(TTF is calculated here for ideal gaps, with $\beta_0 = 0.12$ and $\beta_0 = 0.17$)

4-gap Ladder Resonator (β_0=0.17)

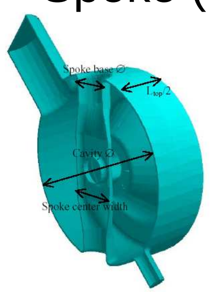
Frequency	**352 MHz**
Accelerating field flatness (between central and end cells)	**96 %**
$B_{s,p}$	**65 mT (set as limit) @ the coupling hole**
B at the flanged joint	**1.5 mT**
$E_{s,p}$	**25 MV/m** (reas. limit 25÷30 MV/m)
Energy gain at β_0 = 0.12	**1.68 MeV/q**
Accelerating Field E_0	**8 MV/m**
Beam Loading	**6÷8 kW**
U/E_a^2	**89 mJ/(MV/m)^2**
Rf coupling (coupling holes)	**0.7 %**
Q - @ 4 K (assumed)	**5 x 10^8**
Geometrical factor G (Ω)	**62 Ω**
$B_{s,p}/E_0T$	**8.7 mT/MV/m**
Rf power dissipation (@ Q = 5 x 10^8)	**10 W**

Which cavity to squeeze in the available space (L_{int}=0.2 m)?

Common reference: H_{pk} < 65 mT, E_{pk} < 30 MV/m

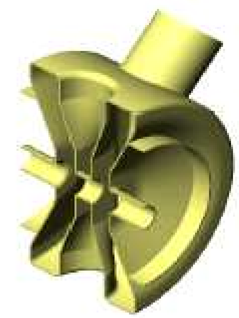
2-gap options

- HWR, QWR conical and cylindrical: E_{pk}/E_a ~5, ΔW < 0.6 MV
- Spoke (examples)



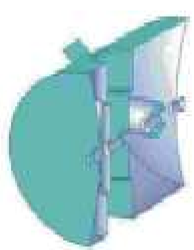
G. Olry et al., IPN-Orsay
EPAC2002, p. 2691

352 MHζ, β_0 **= 0.19**
E_{pk}/E_a = 3.56
E_a = 8.4 MV/m



DESIGN OF A β=0.175 **2-GAP SPOKE RESONATOR***
F.L.Krawczyk et al., SRF2001
http://conference.kek.jp/SRF2001/

3-gap options



K.W. Shepard et al., ANL
SRF2001
345 MHz, β_0 = 0.39

V. Andreev et al., INFN-LNL
EPAC2002, p. 2208

352 MHz, β_0 **= 0.13**
E_{pk}/E_a = 4.65
Ea = 4.77 MV/m